

Highlights of the VERITAS Blazar Program

Wystan Benbow* and the VERITAS Collaboration[†]

*Harvard-Smithsonian Center for Astrophysics, 60 Garden St MS-20, Cambridge, MA 02138, USA

[†]<http://veritas.sao.arizona.edu/>

Abstract.

The VERITAS array of 12-m atmospheric-Cherenkov telescopes in southern Arizona began full-scale operations in 2007, and is one of the world's most-sensitive detectors of astrophysical VHE ($E > 100$ GeV) γ -rays. Approximately 50 blazars are known to emit VHE photons, and observations of blazars are a major focus of the VERITAS Collaboration. Nearly 2000 hours have been devoted to this program and ~ 130 blazars have already been observed with the array, in most cases with the deepest-ever VHE exposure. These observations have resulted in 21 detections, including 10 VHE discoveries. Recent highlights of the VERITAS blazar observation program, and the collaboration's long-term blazar observation strategy, are presented.

Keywords: Gamma-ray Observations; Active and peculiar galaxies and related systems

PACS: 95.55.Pw; 98.54.Cm

Blazars are a class of AGN with relativistic jets pointed along the line of sight to the observer, and are the most numerous class of VHE source. Both sub-classes of blazars, BL Lac objects and Flat Spectrum Radio Quasars (FSRQs), are detected at VHE. Nearly 80% of the VHE blazar population exhibits VHE flux variability. These variations occur on time scales from minutes to years, but are typically only a factor of 2 to 3. The photon spectra of the observed VHE emission is often soft ($\Gamma_{obs} \sim 2.5 - 4.6$), largely due to the attenuation of VHE photons on the extragalactic background light (EBL).

Fermi-LAT has detected almost every VHE blazar. By combining VHE and LAT spectra, the highest-energy peak of the double-humped blazar spectral energy distributions (SEDs) is completely resolved. By combining this with X-ray and optical data, sampling the lower-energy peak, it is possible to constrain source models. VHE blazar studies can also lead to strong new constraints on the EBL and the intergalactic magnetic field (IGMF), and provide insight into the origin of ultra-high-energy cosmic rays.

Approximately 80% of the known VHE blazars are high-frequency-peaked BL Lac objects (HBLs). The SEDs of these HBLs can usually be fit by a synchrotron self-Compton (SSC) model. There are indications that the VHE emission of intermediate and low-frequency peaked BL Lac objects (IBLs and LBLs, respectively) has a different leptonic origin (SSC plus external Compton). However, the current IBL/LBL detections are plagued by poor statistics at VHE, and these non-HBL objects are typically only detected during flaring episodes which might have a different physical origin.

THE VERITAS BLAZAR PROGRAM

VERITAS [1] is sensitive to astrophysical γ -rays in the energy range between ~ 100 GeV and ~ 30 TeV. The array is used to take ~ 1000 h of good-weather data each year, and can detect a 1% Crab Nebula flux source at zenith in < 25 h. The typical systematic errors on VERITAS measurements are 0.1 for the photon index and 20% in the integral flux.

TABLE 1. The 21 blazars detected at VHE with VERITAS. The 10 VHE discoveries are marked with †. The long-term monitoring targets are shown along with their reason for inclusion in the program and the current annual exposure goals. Both the targets and the exposures may evolve. The LBL S5 0716+714 is also monitored (10 h goal), but is not yet detected by VERITAS.

| Blazar | z | Type | $\log_{10}(v_{\text{synch}})$ [4] | Long-term Monitoring |
|-------------------|-------------------|------|-----------------------------------|----------------------|
| Mrk 421 | 0.030 | HBL | 18.5 | Bright HBL (15 h) |
| Mrk 501 | 0.034 | HBL | 16.8 | Bright HBL (15 h) |
| 1ES 2344+514 | 0.044 | HBL | 16.4 | Bright HBL (5 h) |
| 1ES 1959+650 | 0.047 | HBL | 18.0 | Bright HBL (5 h) |
| BL Lac | 0.069 | LBL | 14.3 | Non-HBL (10 h) |
| W Comae† | 0.102 | IBL | 14.8 | Non-HBL (10 h) |
| RGB J0710+591† | 0.125 | HBL | 21.1 | EBL / IGMF (25 h) |
| H 1426+428 | 0.129 | HBL | 18.6 | EBL / IGMF (25 h) |
| 1ES 0806+524† | 0.138 | HBL | 16.6 | — |
| 1ES 0229+200 | 0.140 | HBL | 19.5 | EBL / IGMF (25 h) |
| 1ES 1440+122† | 0.162 | IBL | 16.5 | — |
| RX J0648.7+1516† | 0.179 | HBL | — | — |
| 1ES 1218+304 | 0.184 | HBL | 19.1 | EBL / IGMF (25 h) |
| RBS 0413† | 0.190 | HBL | 17.0 | — |
| 1ES 0414+009 | 0.287 | HBL | 20.7 | EBL / IGMF (25 h) |
| PG 1553+113 | $0.43 < z < 0.50$ | HBL | 16.5 | EBL / IGMF (25 h) |
| 3C 66A† | | IBL | 15.6 | Non-HBL (10 h) |
| B2 1215+30 | | IBL | 15.6 | — |
| PKS 1424+240† | | IBL | 15.7 | — |
| 1ES 0502+675† | | HBL | 19.2 | — |
| RGB J0521.8+2112† | ? | HBL | — | — |

An upgrade of VERITAS was completed in 2012. The new energy threshold is expected to be ~ 60 GeV with an overall sensitivity increase of $\sim 20\%$.

The VERITAS collaboration hopes to improve the understanding of VHE blazars and their related science by expanding the known population and by making precision measurements of their spectra and variability patterns. Contemporaneous multi-wavelength (MWL) observations are a key component of this program since blazars are highly-variable at all wavelengths. Modeling of the resulting SEDs and searches for MWL correlations are used to provide insight into origin of the observed emission.

Since September 2007, VERITAS has observed 128 blazars, for a total of 1981 h (annual average of ~ 400 h) during good weather conditions. Until 2010, $\sim 80\%$ of the VERITAS blazar data were used for VHE discovery observations and follow-up studies of new sources. In 2010, the focus became deep studies of known VHE sources, and $\sim 60\%$ of the data are now devoted to known sources. Target-of-Opportunity (ToO) observations are a key part of the blazar program and typically average 50 h per year. The 21 blazars detected by VERITAS are shown in Table 1; see [2, 3] for more details.

Recent Highlights from the VERITAS Blazar Program

VERITAS has regularly observed BL Lacertae (an LBL) since the start of the 2010-11 season. It is not usually bright enough to be detected at VHE. However, in June 2011, the tail of a bright VHE flare was observed. The peak VHE flux observed was 125% of

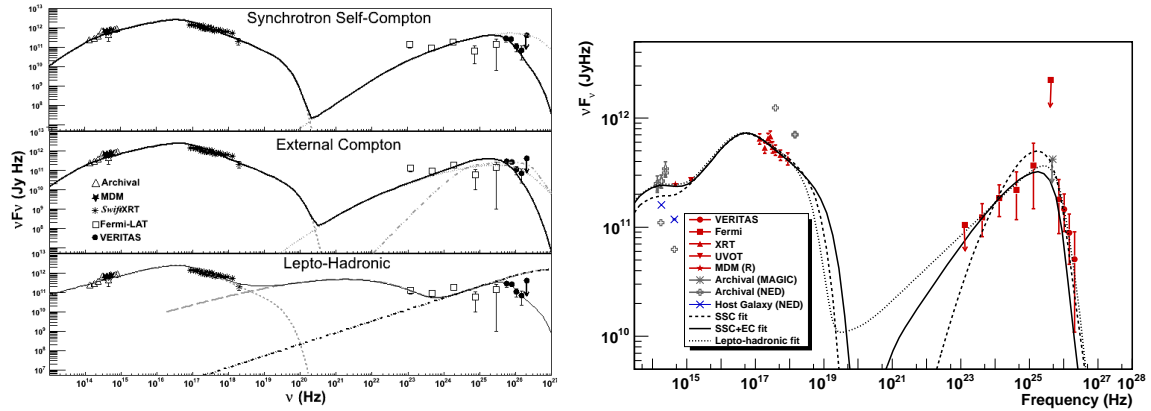


FIGURE 1. The SEDs of (Left) 1ES 0414+009 [6] and (Right) RBS 0413 [7].

the Crab Nebula flux, and the flare exponentially decayed in $\tau = 13 \pm 4$ minutes. Despite being the brightest VHE flux ever observed from the object, the observed photon index ($\Gamma = 3.6 \pm 0.4$) is consistent with that measured by MAGIC during a lower-flux (3% Crab Nebula) flare in 2006. More details on the VERITAS and other MWL observations of this exceptional flare can be found in these proceedings [5].

The comparatively distant ($z = 0.287$) HBL 1ES 0414+009 is a known VHE emitter and was observed with VERITAS for 56 h of quality-selected live time between 2008 and 2011. These data resulted in the significant detection of a source with flux $\sim 2\%$ of the Crab Nebula flux [6]. The observed spectrum is soft $\Gamma = 3.4 \pm 0.5$, largely due to the effects of EBL absorption. Although an HBL, its SED (see Figure 1) is not well fit by one-zone leptonic models; a lepto-hadronic model provides a better fit.

Since September 2007, ~ 1260 h of VERITAS data were devoted to the discovery and follow-up observations of more than 100 blazars at VHE. The candidates observed are largely HBLs, but also include IBLs, LBLs, FSRQs, and Fermi-LAT sources likely associated with blazars. From 2007-09, the discovery program [8] focused on nearby (redshift, $z < 0.3$) X-ray-bright HBLs, IBLs, and FSRQs recommended in the literature and nearby EGRET-detected blazars. Some of the X-ray-bright targets were objects that met the selection criteria applied in the literature, but were first reported in later catalogs. Following the release of the first Fermi-LAT catalog of MeV-GeV-bright blazars in 2009 [9], the discovery program has focused on objects detected by Fermi-LAT [10].

These observations resulted in the VERITAS discovery of VHE γ -ray emission from 6 HBLs and the first 4 IBLs known to emit VHE photons [2]. The initial observations of 60% of these new VHE sources were motivated by the X-ray/EGRET-based selection criteria, and all these objects are detected by Fermi-LAT. In general, these new sources have soft VHE spectra ($\Gamma_{avg} = 3.5$), and only three exhibit strong VHE flux variability. The VHE flux upper limits derived from the unsuccessful discovery observations are typically less than 2% of the Crab Nebula flux and often the strictest yet.

The successful VHE discovery observations [11] of RX J0648.7+1516 were motivated by the identification of a cluster of $E > 10$ GeV photons in the Fermi-LAT data. A total of 19 h of quality-selected live time was taken in March-April 2010. Significant VHE emission ($\Gamma = 4.4 \pm 0.8$, $\sim 3\%$ Crab Nebula flux) was detected at the position of

RXJ0648.7+1516, an unidentified radio, optical and X-ray emitter. Follow-up optical spectroscopy of this object yielded a continuum-dominated spectrum typical of BL Lac objects and weak absorption lines compatible with $z = 0.179$. The SED of this blazar indicates it is an HBL, but it is not well fit by an SSC model.

RBS 0413 is a bright HBL, at $z = 0.190$, that was initially targeted based on its inclusion in the Sedentary Survey [12]. It was observed for ~ 26 h of quality-selected live time between 2008 and 2010 [7]. The data yielded the detection of a soft-spectrum ($\Gamma = 3.2 \pm 0.7$) source with $\sim 1\%$ Crab Nebula flux. Its SED, shown in Figure 1, is again not well described by a SSC model. The modeling favors the inclusion of an additional external-Compton (EC) component, and can also be fit by a lepto-hadronic scenario.

THE LONG-TERM BLAZAR OBSERVATION STRATEGY

In 2010, VERITAS began a systematic campaign to acquire deep exposures on 14 VHE blazars. Much of these data are acquired via regular monitoring exposures, and data taking is intensified during any flaring behavior. Regular simultaneous MWL observations are also organized. The 14 selected blazars are indicated in Table 1, and include:

- 6 comparatively distant, hard-VHE-spectrum HBLs for EBL and IGMF studies.
- 4 bright HBLs to easily enable MWL studies with high VHE statistics. These may also have the highest likelihood for exhibiting greater than Crab Nebula flux flares.
- 4 non-HBLs to provide insights into the blazar sequence, to discover their low VHE states, and to study future VHE flares.

The total targeted exposure on these 14 VHE blazars is ~ 220 h per year. A discovery program will also continue, with a goal of ~ 100 h per year. It will focus on Fermi-LAT selected objects but will have a larger emphasis on higher-risk / higher reward targets that may require deep exposures. An active ToO program on both known VHE sources and VHE discovery candidates will also be maintained. The triggers will be based on optical, X-ray, MeV-GeV gamma-ray and TeV gamma-ray flares. The VERITAS collaboration hopes to increase the amount of blazar ToO data to ~ 100 h per year.

Acknowledgments This research is supported by grants from the U.S. Department of Energy Office of Science, the U.S. National Science Foundation and the Smithsonian Institution, by NSERC in Canada, by Science Foundation Ireland (SFI 10/RFP/AST2748) and by STFC in the U.K. We acknowledge the excellent work of the technical support staff at the Fred Lawrence Whipple Observatory and at the collaborating institutions in the construction and operation of the instrument.

REFERENCES

1. J. Holder, *Proc. of the 32nd ICRC (Beijing)*, 2011; arXiv:1111.1225
2. W. Benbow, *Proc. of the 32nd ICRC (Beijing)*, 2011; arXiv:1110.0040
3. W. Benbow, *Proc. of the 32nd ICRC (Beijing)*, 2011; arXiv:1110.0038
4. E. Nieppola et al., *A&A*, **445**, 441, 2006
5. T. Nelson, *these proceedings*, 2012
6. E. Aliu et al., *ApJ*, **755**, 118, 2012
7. E. Aliu et al., *ApJ*, **750**, 94, 2012
8. W. Benbow, *Proc. of the 31st ICRC (Lodz)*, 2009; arXiv:0908.1412
9. A. Abdo et al., *ApJ*, **700**, 597, 2009
10. P. Nolan et al., *ApJS*, **199**, 31, 2012
11. E. Aliu et al., *ApJ*, **742**, 127, 2011
12. P. Giommi et al., *A&A*, **434**, 385, 2005